AFRL-RI-RS-TR-2015-133

FREQUENCY DIVERSE ARRAY COMPONENT CHARACTERIZATION: AN EVALUATION OF LOW-COST RF COMPONENTS FOR TESTING FREQUENCY DIVERSE ARRAY ANTENNAS USED IN SECURE COMMUNICATION INVESTIGATIONS

JUNE 2015

INTERIM TECHNICAL REPORT

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

STINFO COPY

AIR FORCE RESEARCH LABORATORY
INFORMATION DIRECTORATE

■ **AIR FORCE MATERIEL COMMAND** ■ **UNITED STATES AIR FORCE** ■ **ROME, NY 13441**

NOTICE AND SIGNATURE PAGE

AFRL-RI-RS-TR-2015-133 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

FOR THE DIRECTOR:

/ S /
RICHARD MICHALAK, Chief
Information Transmission Branch

/ S /
MARK LINDERMAN
Technical Advisor, Computing
& Communications Division
Information Directorate

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
JUNE 2015	INTERIM TECHNICAL REPORT	JAN 2015 – APR 2015

4. TITLE AND SUBTITLE

FREQUENCY DIVERSE ARRAY COMPONENT CHARACTERIZATION: AN EVALUATION OF LOW-COST RF COMPONENTS FOR TESTING FREQUENCY DIVERSE ARRAY ANTENNAS USED IN SECURE COMMUNICATION INVESTIGATIONS

5a. CONTRACT NUMBER IN-HOUSE (R1MQ)

5b. GRANT NUMBER N/A

5c. PROGRAM ELEMENT NUMBER 62788F

6. AUTHOR(S)

Thomas Scatko and William Lipe

5d. PROJECT NUMBER CLSR

5e. TASK NUMBER IN

5f. WORK UNIT NUMBER HO

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory/RITE
525 Brooks Road
Rome NY 13441-4505

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory/RITE
525 Brooks Road
Rome NY 13441-4505

10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/RI

11. SPONSOR/MONITOR'S REPORT NUMBER AFRL-RI-RS-TR-2015-133

12. DISTRIBUTION AVAILABILITY STATEMENT

Approved for Public Release; Distribution Unlimited. PA# 88ABW-2015-2632
Date Cleared: 26 MAY 2015

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This Technical Report describes some of the transmit instrumentation, that was assembled using relatively inexpensive commercial-off-the-shelf (COT) components, for use in investigating the performance of frequency diverse array (FDA) antennas for secure communications. Brief descriptions of the bench-level set-ups used for characterizing the transmit waveform generation instrumentation are provided. Test results are included to give some indication of expected level of performance.

15. SUBJECT TERMS
Frequency Diverse Array (FDA), Commercial-off-the-shelf (COT), Low Probability of Intercept (LPI)

16. SECURITY CLASSIFICATION OF: a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** / **19b. TELEPHONE NUMBER** *(Include area code)*
U	U	U	UU	36	**THOMAS SCATKO** / **NA**

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

CONTENTS

FIGURES

TABLES

1.0 SUMMARY

This Technical Report describes transmit instrumentation assembled, using relatively inexpensive commercial-off-the-shelf (COT) components, for use in investigating the performance of frequency diverse array (FDA) antennas for tactical communications. Brief descriptions of the test set-ups are provided. Test results are included for gauging expected operational performance for field tests and measurements.

2.0 Introduction

New signal processing techniques and new array antenna designs will allow for the deployment of communication and radar systems capable of transmitting sophisticated signals that vary jointly as a function of frequency, space, and time. Typically, when one considers low probability of intercept (LPI) transmissions it is usually in terms of waveforms that employ spread spectrum and/or frequency hopping techniques or, perhaps in the case of radars, array antennas that exhibit either low or ultra-low sidelobe pattern characteristics. In most instances, LPI waveforms and LPI antennas are designed independent of one another. However, newer LPI techniques take advantage of joint frequency, space, and time performance dependencies of the waveform and array antenna to create signals that are extremely difficult to detect, characterize and identify.

The objective of this in-house effort is to assemble a *bare-bones* multi-channel transmitter, capable of generating a limited set of waveforms, for the purpose of measuring signal characteristics with respect to frequency, space and time variation for evaluation of FDA utility in military radio frequency (RF) applications i.e., secure communications and radar. Rather than apply a linear phase shift across an array of radiating antenna elements an incremental frequency adjustment is made to each transmit channel to generate an antenna pattern that is a function of range, time and angle. [1 - 5] Figures 1 and 2 illustrate the respective differences in the array factors calculated for an eight-element electronically scanned array (ESA) and an eight-element frequency diverse array (FDA).

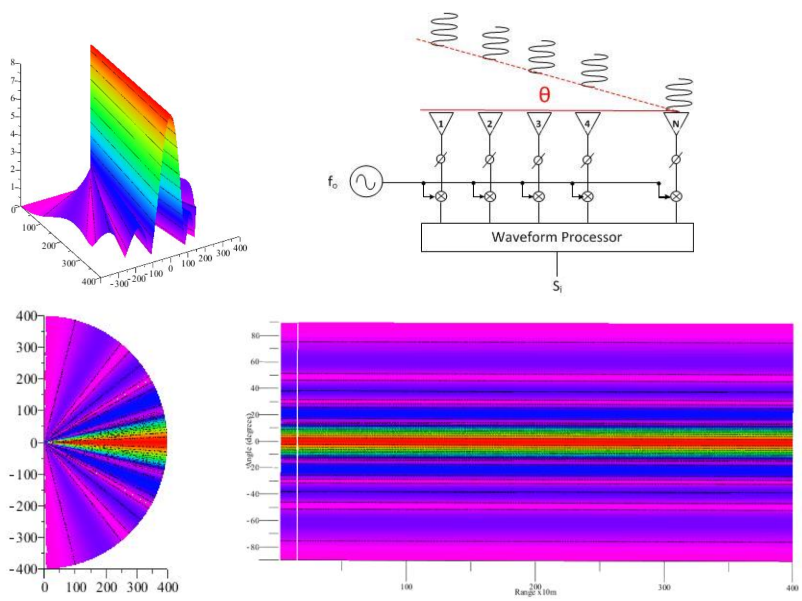


Figure 1: Conventional Electronically Scanned Array CW Pattern.

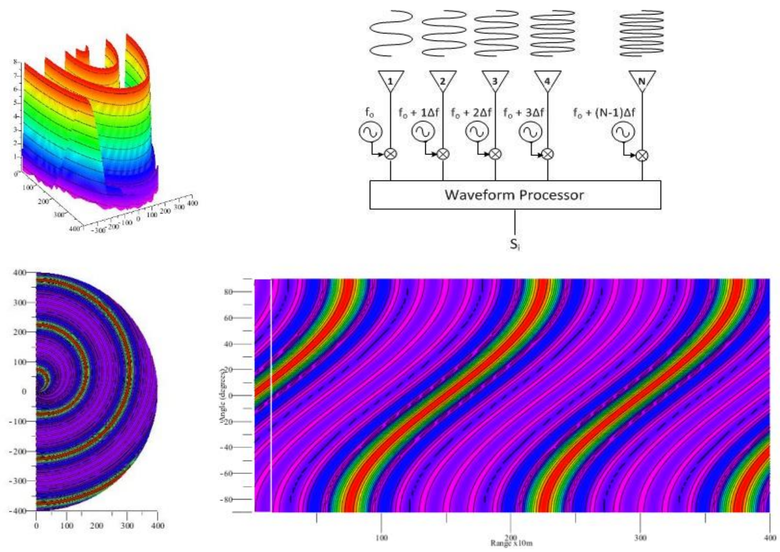


Figure 2: Frequency Diverse Array CW Pattern.

In each of the two Figures the upper-left pattern is a three-dimensional cylindrical plot of the array factor, the lower-left pattern is a two-dimensional cylindrical plot graphed in range versus cross-range dimensions, and the lower-right plot is the array factor plotted in angle versus range dimensions. The differences in beam pattern shape with respect to range and angle are readily apparent. Control of the FDA pattern and measurement of pattern change as a function of time will be affected by system component performance characteristics. Of primary importance is both the setting and control of the incremental change in frequency established across the transmit elements. Also, waveform generation and timing control will impact how pattern measurements are made. Given that this effort makes use of relatively inexpensive COTS components their performance may negatively impact measurement outcomes.

This Technical Report examines the performance of: a low-cost waveform generator for its ability to generate a simple pulse with controlled low-jitter triggering; a low-cost continuous wave (CW) signal synthesizer for its ability provide controlled frequency offsets; and a GPS timing system for its ability to provide a stable 1 PPS signal used in data collection synchronization. Characterization measurements were somewhat limited by the poor quality test equipment available for laboratory use.

3.0 METHODS, ASSUMPTIONS, AND PROCEDURES

One of the goals of this effort was to develop a simple, low-cost test set-up for investigating and assessing FDA technology for potential military applications. Meeting these design objectives required the use of on-hand components and instrumentation whenever possible. Likewise, a prime determining factor when selecting and purchasing parts and supplies was cost. The design presented in the following sections is reflective of these constraints.

3.1 Test Set-up

The test set-up employed for generating a simple set of frequency-offset waveforms is illustrated in Figure 3. While the design allows for N-number of transmit channels only four were implemented here. Key instruments are shown in Figure 4 during bench-top testing and identified in Table 1.

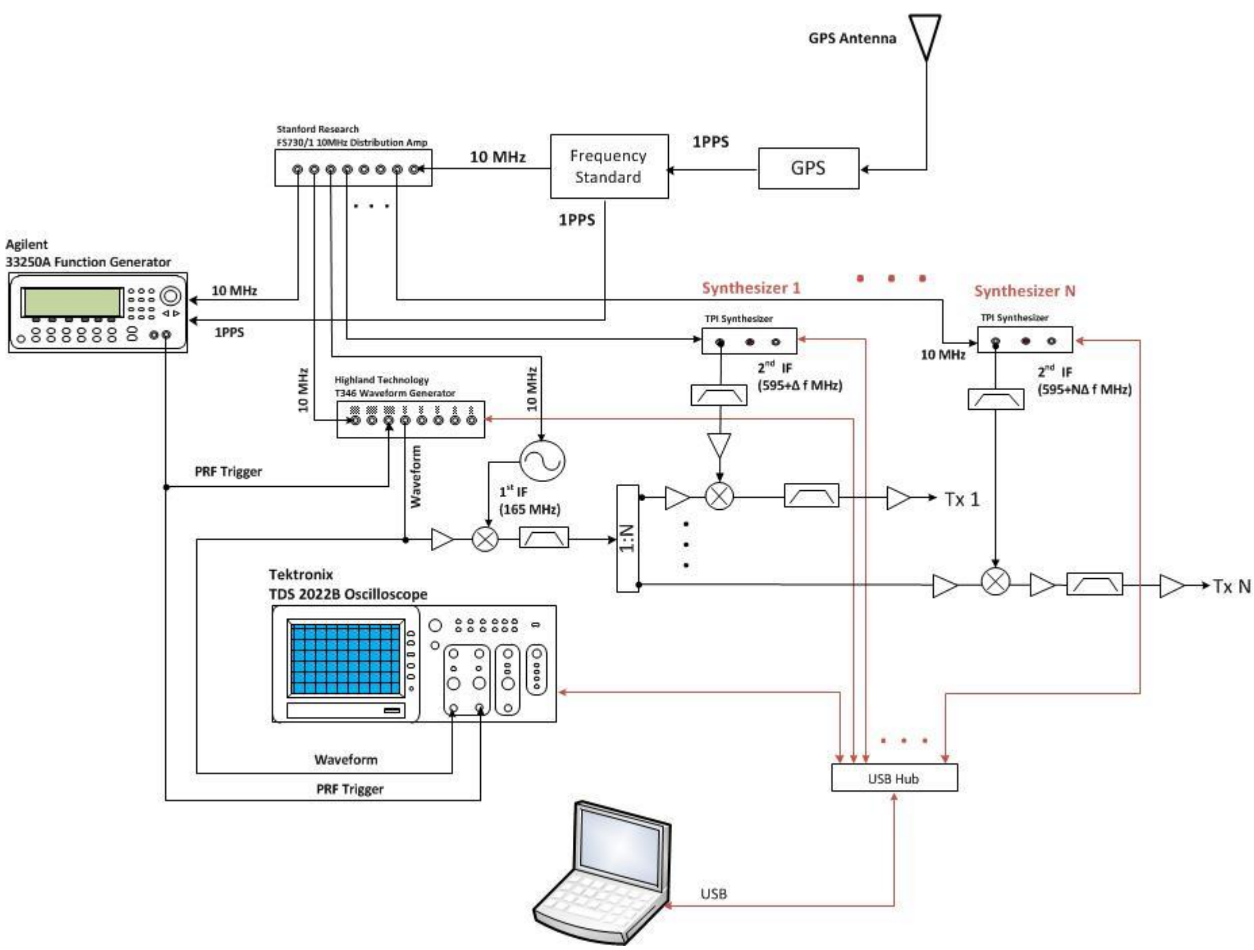


Figure 3: Waveform Generation Test Schematic.

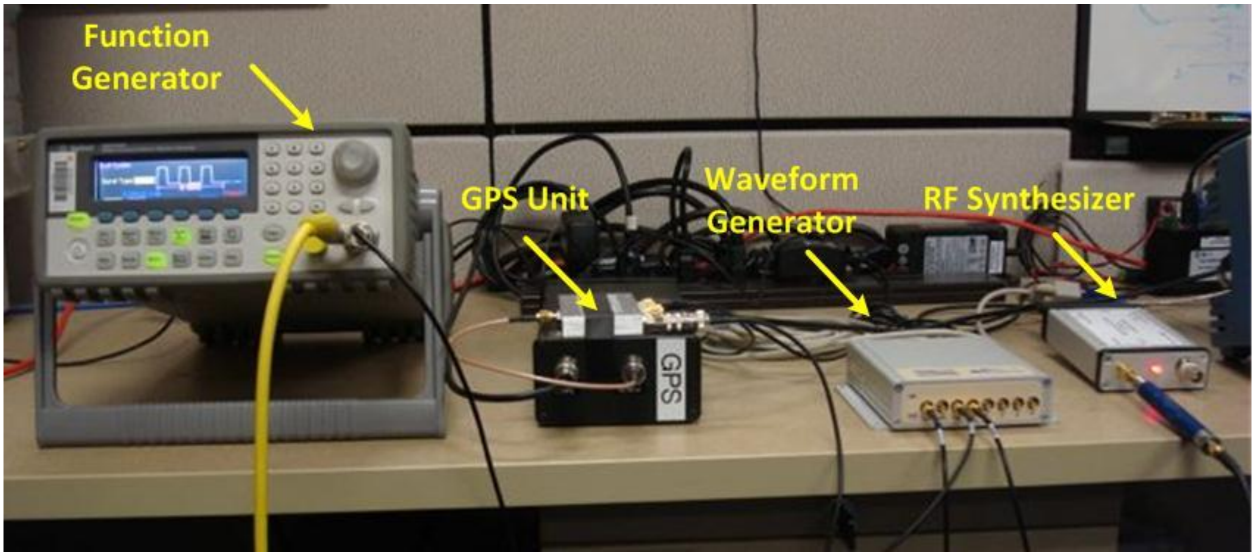


Figure 4: Waveform Generation Benchtop Test Set-up.

Table 1: Instrument List.

Instrument Name:	Part No:	Manufacturer:	Note:
Function Generator	33250A	Agilent	On-hand Laboratory Item
GPS Disciplined Clock Module w/Antenna	Trimble® Mini-T™ Evaluation Board	Trimble	On-hand item/Project Residue installed in a chassis in-house Est. Cost: $ 1200.00
Waveform Generator	T346	Highland Technology	On-hand Item/Project Residue Est. Cost: $ 4800.00
RF Signal Generator	TPI Synthesizer	Trinity Power Inc.	Four(4) procured for effort $ 280.00 ea.
Oscilloscope	TDS2022B	Tektronix	On-hand Laboratory Item
12 Port USB Hub	USBG-12U2ML	USBGEAR	One (1) procured for effort $ 88.00
Distribution Amplifier	FS730/1	Stanford Research	One procured for effort $ 1275.00
10 MHz Reference	PRS10	Stanford Research	One procured for effort $2950.00

A simple, low-cost waveform generator unit used to create either a burst waveform consisting of unmodulated pulses or a continuous wave (CW) signal. Generating a burst requires the input of gating pulses that are output by a function generator that is in-turn triggered by a GPS 1 PPS input signal (reference the circuit diagram provided in Figure 3). Function generator settings determine the pulse repetition interval (PRI), pulse repetition frequency (PRF) and pulse width, as well as the number of pulses in any particular burst. Figure 5 illustrates a typical triggering/gating sequence.

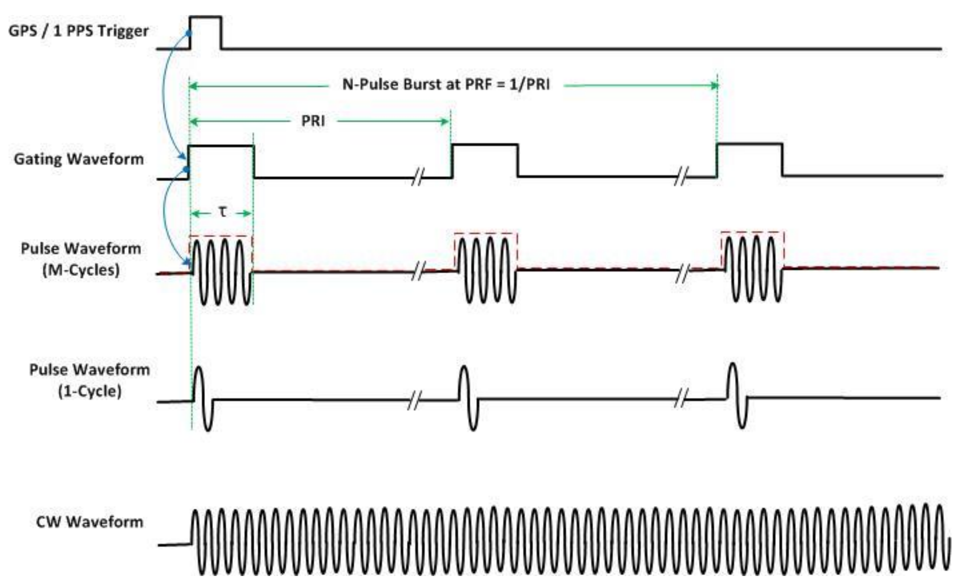


Figure 5: Transmit Waveforms.

3.2 Waveform Generator

The waveform generator (WG) unit includes four (4) independent direct-digital synthesis (DDS) based waveform generators, the outputs of which are available on the front panel of the unit (designated as channels 0, 1, 2 and 3). The unit also has four (4) additional internal waveform generator channels, the outputs of which are not externally available, that can be used as modulation, summing, or control sources. Also available on the WG's front panel are inputs for and external reference clock and external trigger source – both of which are utilized in this set-up. An RS-232 interface is used for instrument control. The WG unit is shown in Figure 6.

Figure 6: Waveform Generator.

A freeware serial port terminal emulation program (Terminal™ v1.91b) was loaded on the set-up’s laptop computer to provide a quick and simple means for communicating with the waveform generator unit via an RS-232 port. A screenshot of the Terminal™ GUI is provided in Figure 7.

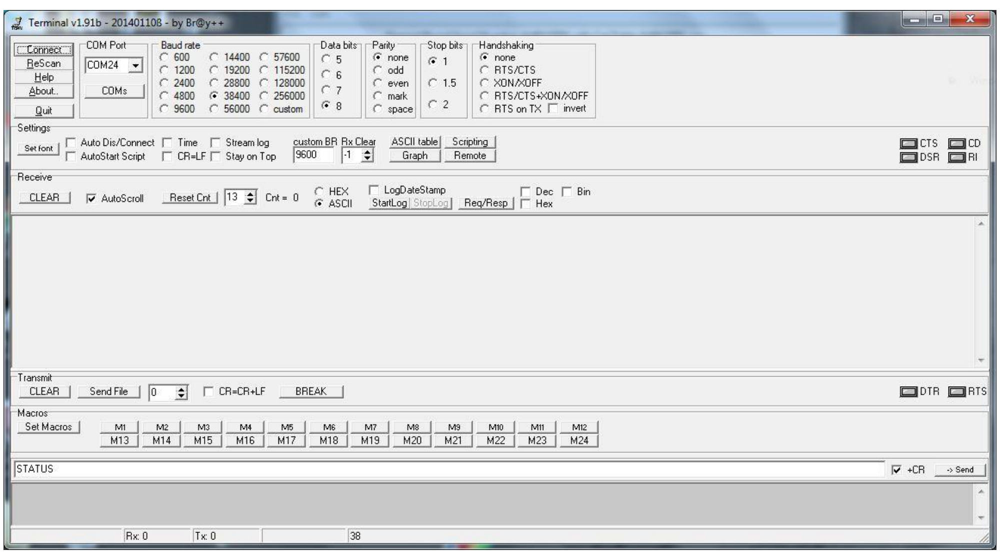


Figure 7: GUI Screenshot – Terminal™ v1.91b.

3.3 RF Synthesizer

A low-cost RF synthesizer module was selected for use in frequency shifting of the 160 MHz intermediate frequency (IF) band signal up to the final RF transmit frequency. This unit utilizes an Analog Devices™ PPL integrated circuit ADF4351©. Specifications for the unit include: an output frequency range of 35 MHz to 4400 MHz using fractional-N and integer-N synthesizers; phase noise of -91 dBc/Hz measured at 1 GHz and 10kHz offset; typical jitter of 0.4 ps rms; and programmable output power level ranging between +10 dBm and -55 dBm. An external input is provided for a 10 MHz reference signal. The synthesizer module is shown in Figure 8.

Figure 8: RF Signal Synthesizer Module.

The Unit's manufacturer has supplied a simple GUI called *SynthMachine™* which can be loaded for implementing unit control. A screenshot of the supplied GUI is provided in Figure 9.

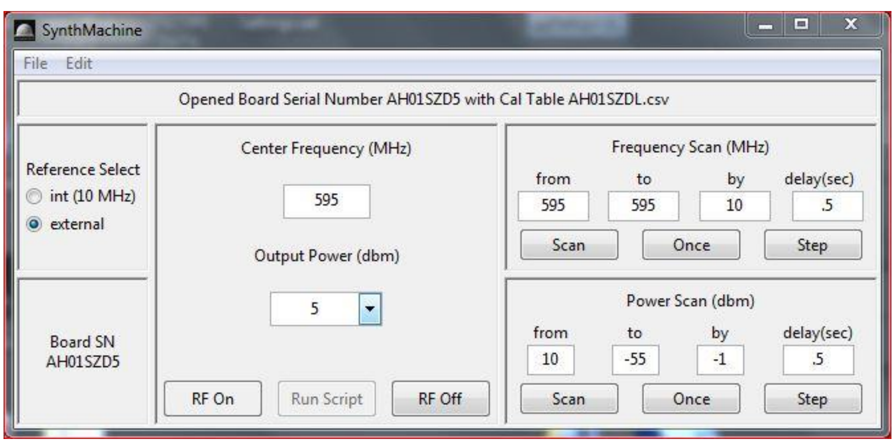
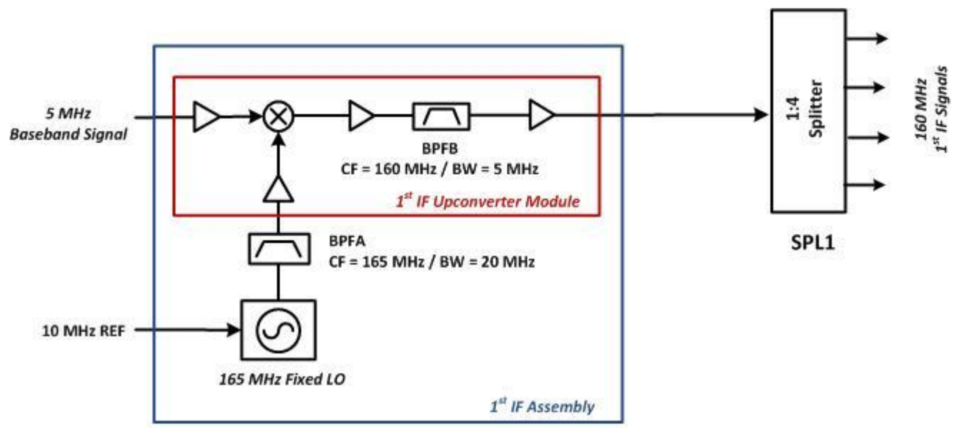


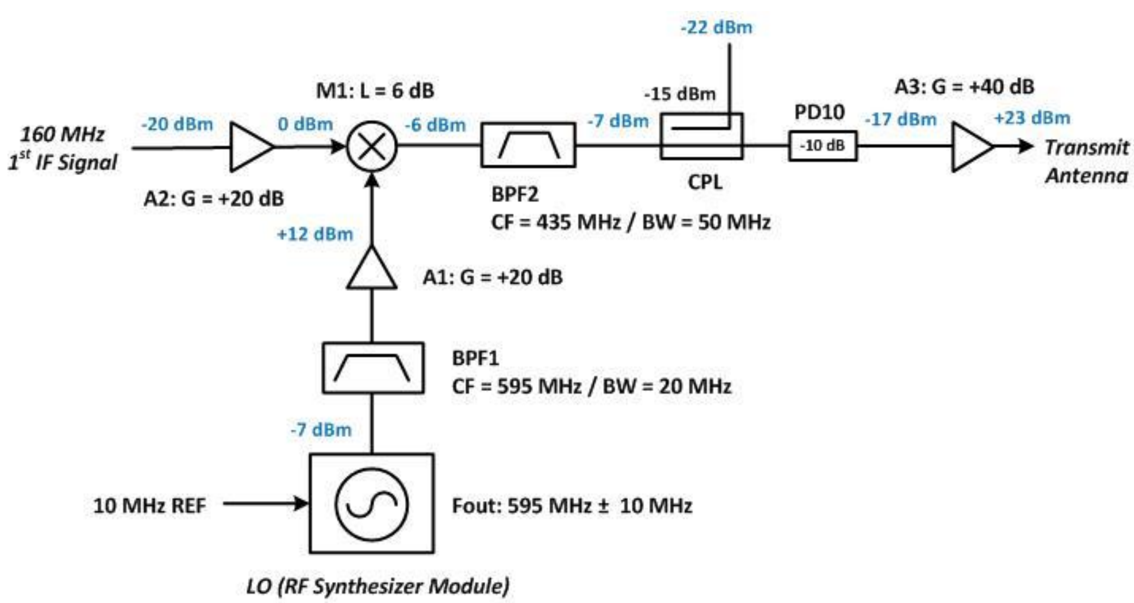
Figure 9: GUI Screenshot – SynthMachine™ control panel.

3.4 RF Up-converter and Power Amplifier

In the chosen configuration a common 160 MHz baseband signal is generated, in the 1st IF up-converter, and then split N-ways which serve as the inputs to N transmit channels. Each 2nd stage channel is identically configured to up-convert from 160 MHz to 435 ± Δf MHz. Here the frequency offset, Δf , is controlled by adjusting the output the 2nd local Oscillator (LO) i.e., the RF Synthesizer module described previously in Section 3.3. A schematic of a typical transmit channel is provided in Figure 10. The 1st Upconverter Module and 1st IF Assemble Unit are project residue and available for re-use at no cost. Key circuit components are identified in Table 2.



A. First IF Stage



B. Second IF Stage

Figure 10: Up-converter Schematic.

Table 2: Transmit Channel Component List.

ID	Name	Part Number	Source	Cost
A1	Low Nosie Amplifier	LNA-1400	RF BAY, Inc.	$170
A2	Low Noise Amplifier	LNA-1400	RF BAY, Inc.	$170
A3	Power Amplifier	MPA-450	RF BAY, Inc.	$500
BP1	Bandpass Filter	5B2-595-20-S11	REACTEL Inc	$414
BP2	Bandpass Filter	3B120-435/T50-0/0	K&L Microwave	$350
M1	Mixer	ZX05-1MHW+	Mini-Circuits	$40
CPL	Coupler	ZEDC-15-2B	Mini-Circuits	$65
LO	LO/RF Synthesizer	TPI Synthesizer	Trinity Power Inc.	$280
PD10	Attenuator	VAT-10+	Mini-Circuits	$14
SPL1	RF Splitter	ZD4PD1-500-N+	Mini-Circuits	$95
			Total Cost/Channel:	$2098

While only four transmit channels are utilized in this experimental set-up, the design can just as easily be expanded to accommodate N-channels by simply multiplying-up the number of transmit circuit boards. In this case the required four channels were assembled and attached, in parallel, to a mounting plate as shown in Figure 11.

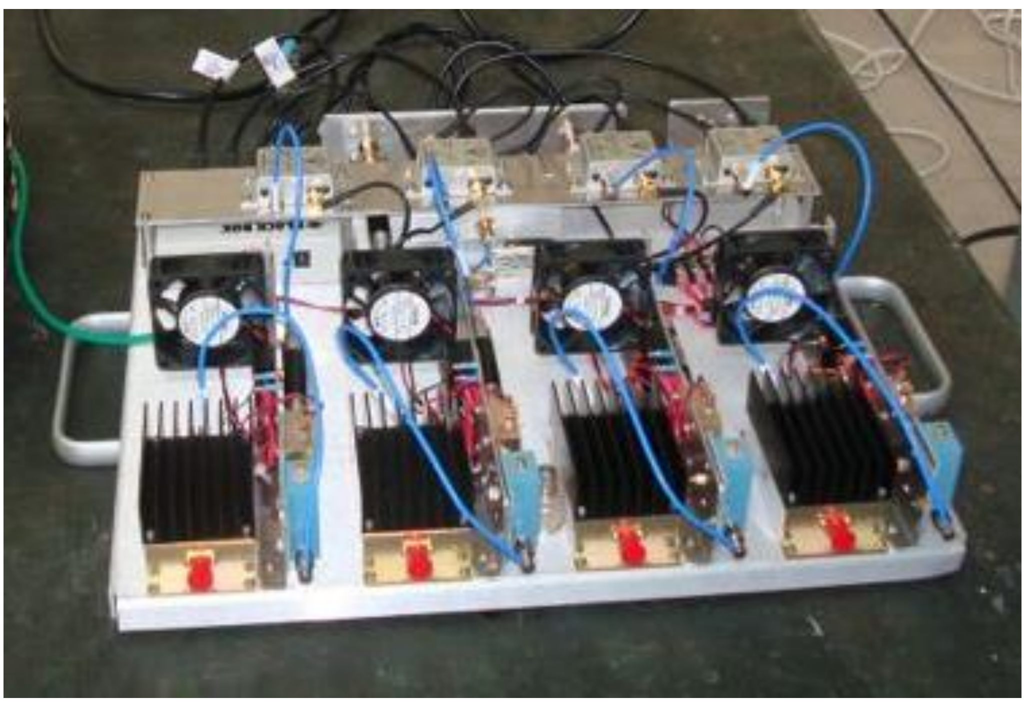


Figure 11: RF Up-conversion (2nd Stage) Circuitry.

3.5 Four Element Array Antenna

A simple four element transmit array antenna was constructed to facilitate FDA field testing. The array elements consist of folded dipoles (Telewave Inc., ANT405D) , designed for operation in the 406 MHz to 512 MHz frequency range, which are mounted to an aluminum trust support structure. Element spacing is roughly ½ wavelength or 27 inches. A mechanical drawing of the array antenna is provided in Figure 12. A photograph of the field installation is provided in Figure 13. The structural design can easily be extended to accommodate increased aperture size i.e, larger element spacing, and greater number of elements.

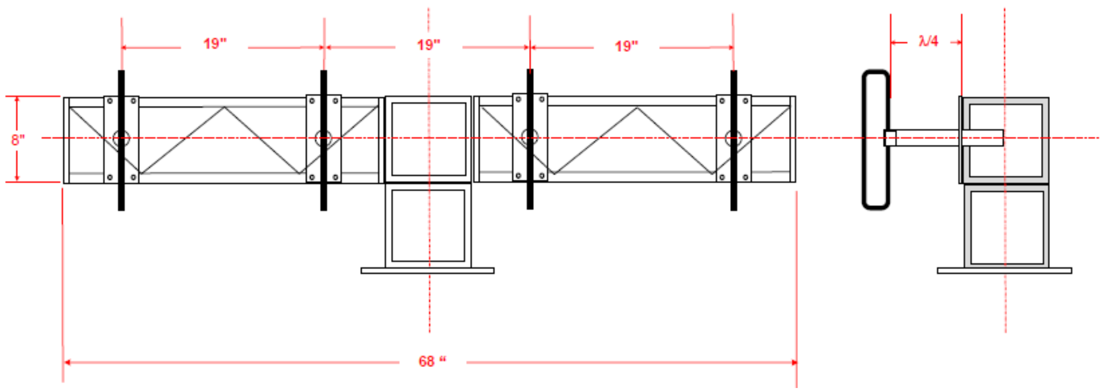


Figure 12: Four-Element Array Transmit Antenna.

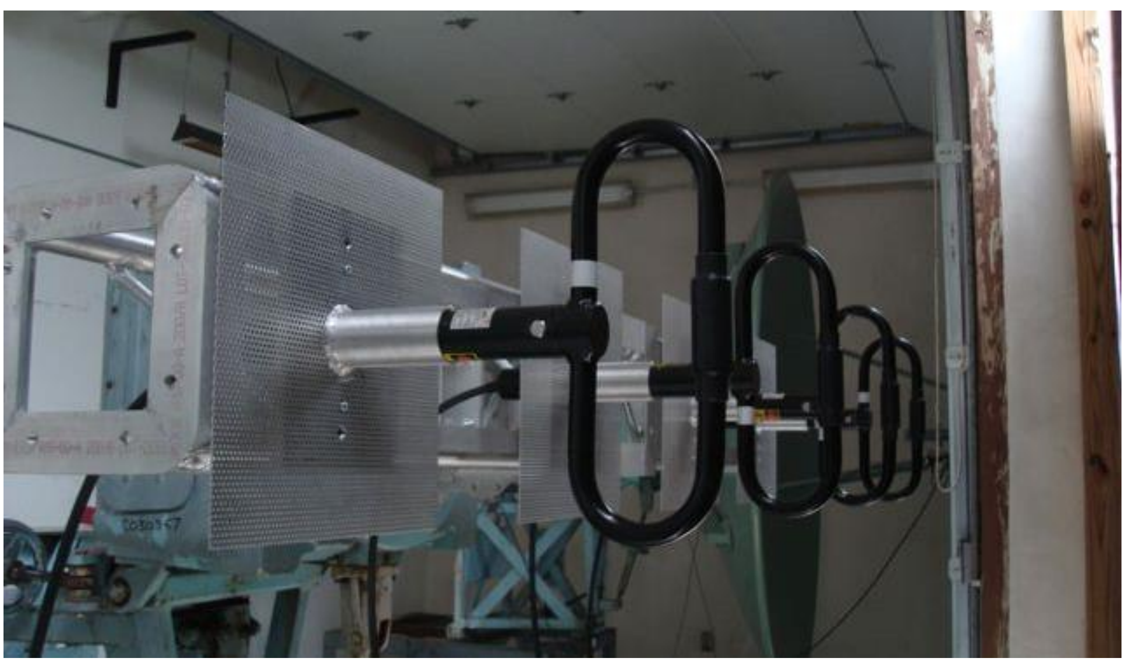


Figure 13: Fielded FDA Antenna.

4.0 Results and Discussion

Measurements were made to characterize the performance of the Waveform Generator and RF Synthesizer modules. Performance results are presented in the sections that follow.

4.1 Waveform Generator Performance

Two waveforms will be used during the initial set of sets: a continuous wave (CW), and a unmodulated CW pulse. The complexity of the waveform i.e., the form of modulation used, is limited by the capabilities of the T346 waveform generator. Synchronization of the transmitter and receivers is accomplished using of 1PPS signals generated by collocated GPS units. Figures 14 through 16 show oscilloscope measurements made of typical pulse waveforms produced using the T346 waveform generator and 33250A function generator. In each case the upper signal trace is that output by the T346 waveform generator while the lower signal trace is generated using the 33250A function generator. The function generator output is used to both as a trigger and a gate which allows for variable pulse widths and a pulse repetition frequency greater than one Hz. The instantaneous bandwidth of the instrumentation is 5 MHz allowing for use of 200 ns pulses which is achievable using the T346 unit. The measured triggering delay is approximately 200 ns.

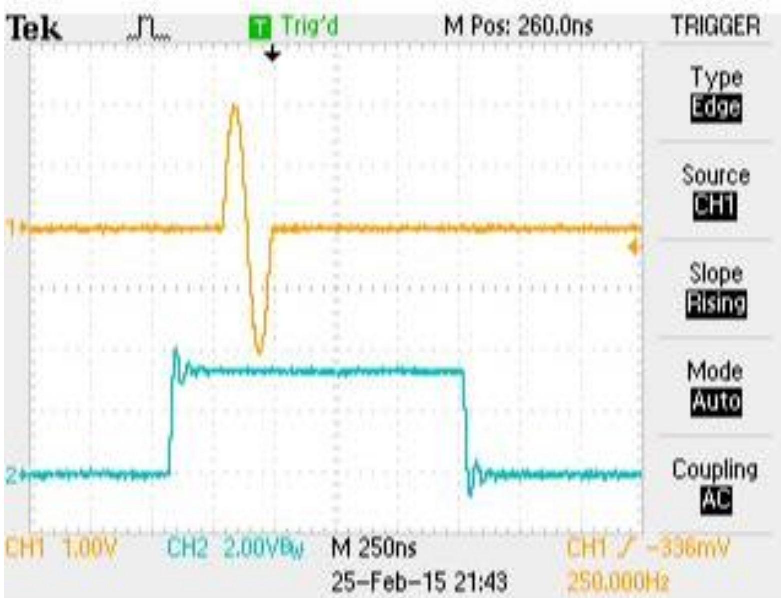


Figure 14: Waveform Generator 5Mhz One Shot Pulse Output.

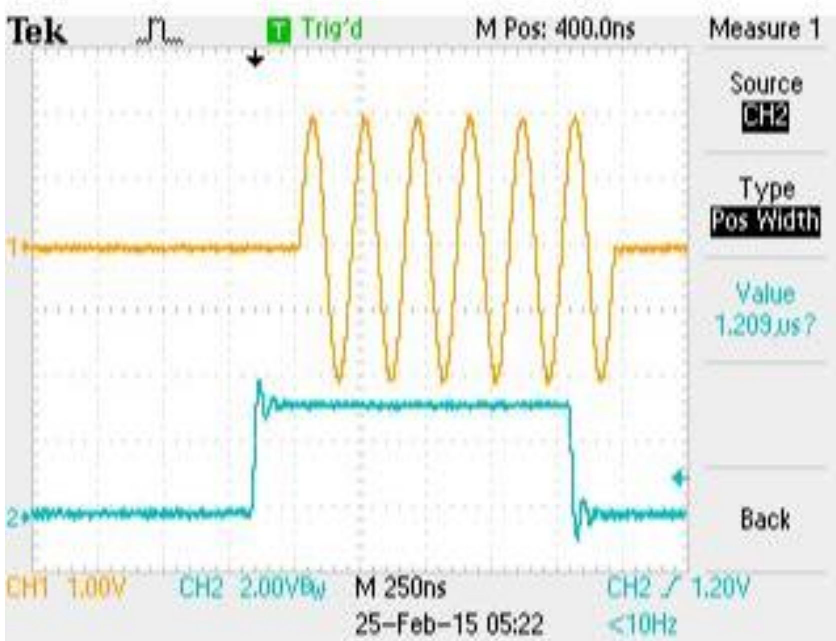


Figure 15: Waveform Generator 5 MHz Gated CW Pulse.

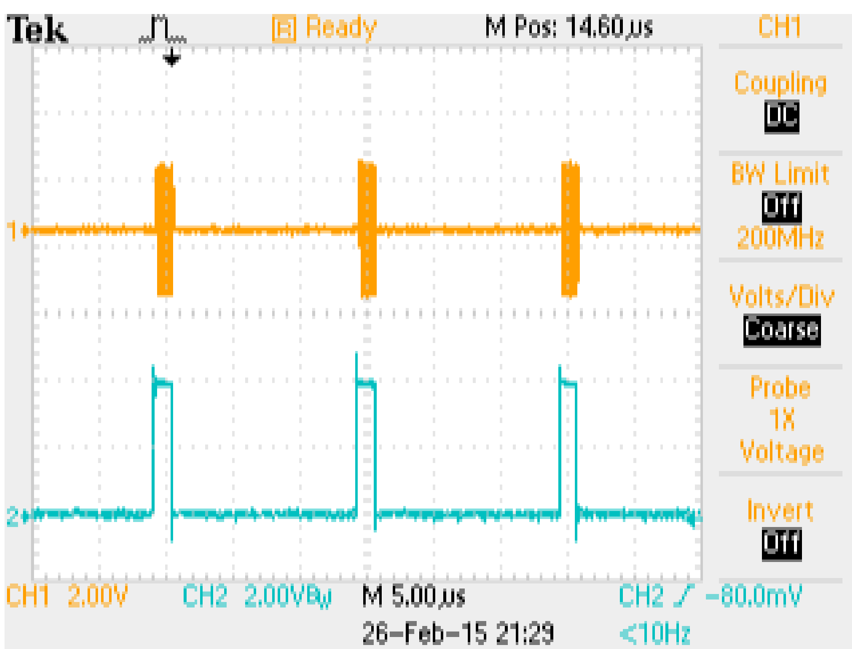
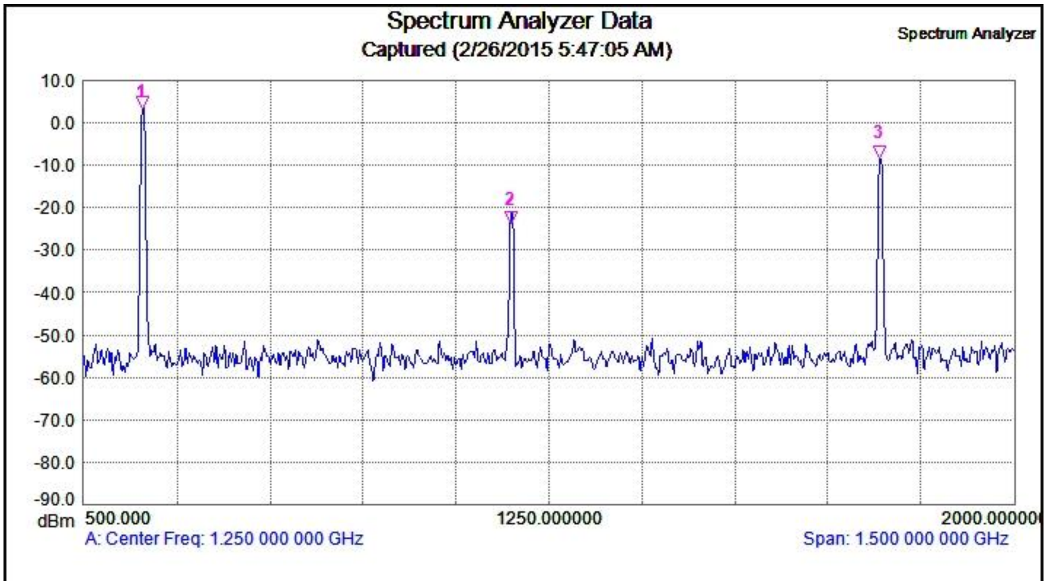


Figure 16: Waveform Generator High PRF 3-Pulse Burst Waveform.

4.2 RF Synthesizer Performance

A low-cost RF synthesizer unit is used as the local Oscillator (LO = 595 MHz ± N ΔF) for frequency shifting the 160 MHz intermediate frequency (IF) signal to 435 MHz ± N ΔF. Measurements were made to determine signal harmonics generated as well as the unit's phase noise level. The spectrums of the unfiltered (595 MHz) signal output is shown in Figure 17 with harmonics clearly present at 1190 MHz and 1785 MHz.



Mkr	Ref	Delta	Ref Freq	Ref Amp	Delta Freq	Delta Amp
1	☐	☐	595.090 974 MHz	3.48 dBm	--	--
2	☐	☐	1.188 363 636 GHz	-23.83 dBm	--	--
3	☐	☐	1.784 727 273 GHz	-8.30 dBm	--	--

Figure 17: TPI Synthesizer RF Output/Unfiltered.

A passband filter centered at 595 MHz, and with a 20 MHz 3dB bandwidth, is used to reduce the harmonic signal levels. The frequency response of one 595 MHz passband filter is shown in Figure 18. The RF synthesizer's filtered output is shown in Figure 19 with signal harmonics attenuated roughly 55 dB which is found to be adequate for performing the frequency translation required in the 2nd IF transmit section.

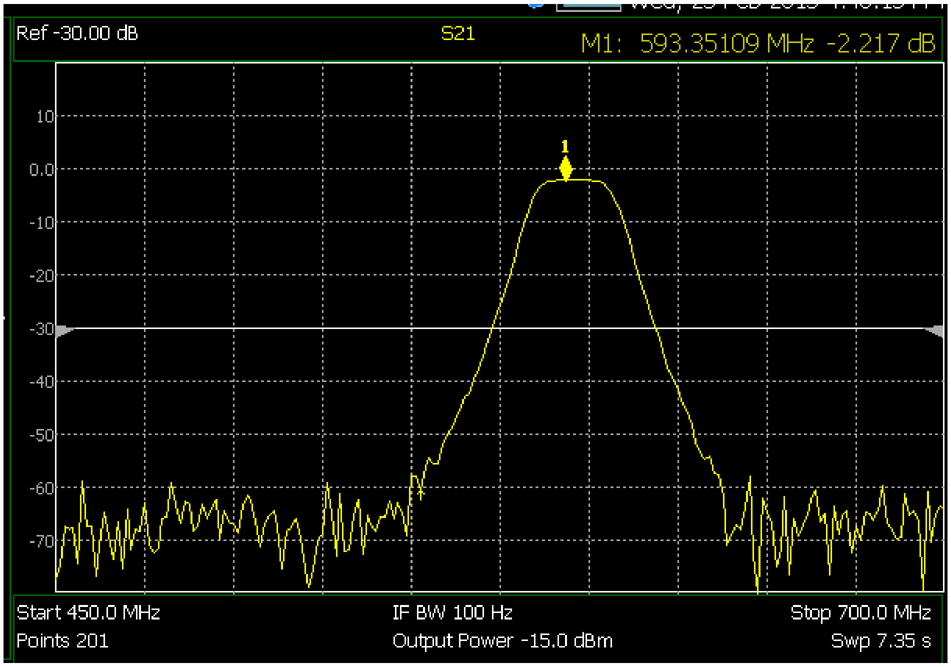


Figure 18: Synthesizer Output Filter Measured Frequency Response.

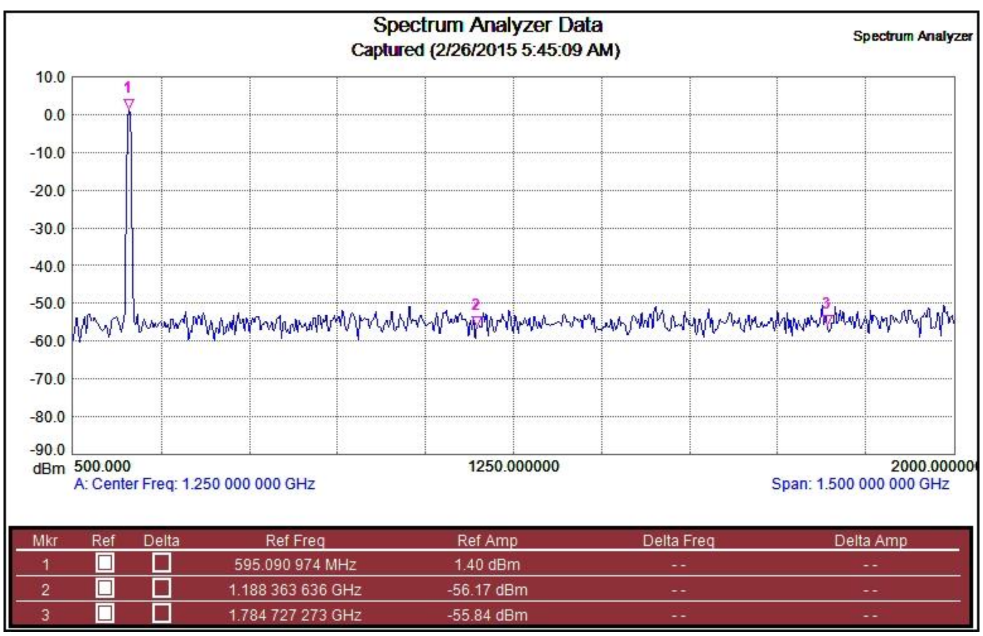
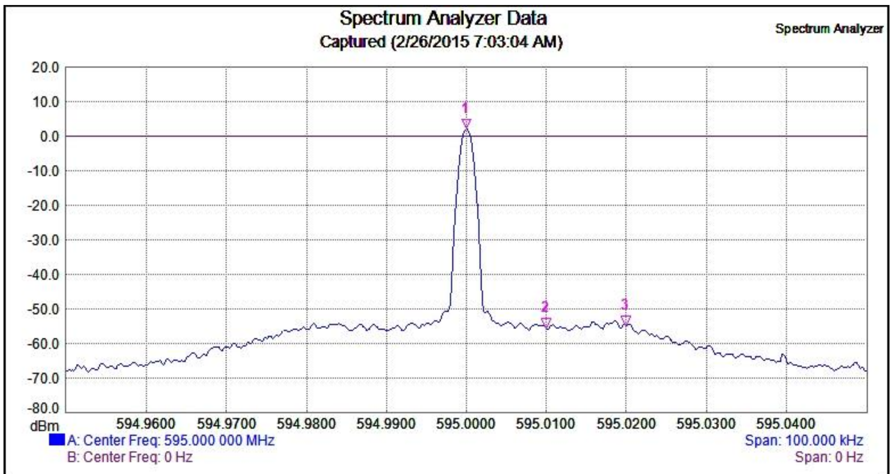


Figure 19: Synthesizer Output/Filtered.

Phase Noise at 595 MHz was measured using a spectrum analyzer with the resolution bandwidth set to 1 kHz and with the instrument's *Max-Hold* setting turned on. As indicated in Figure 20, the noise level at both the 10 kHz and 20 kHz markers is roughly 58 dB below that of the carrier frequency's spectral peak. This terms of spectral density this would be -88 dBc/Hz (i.e., given that the Resolution Bandwidth in dB = 10 log 1000 Hz or 30 dB Hz and subtracting this number from -58 dBc yields -88 dBc/Hz). The manufacturer provides a Phase Noise figure equal to -89 dBc/Hz (measured at 2.4 GHz). By contrast, published data for low phase noise signal source (see Figure 21) indicates that the synthesizer's -88 dBc/Hz figure is rather high.



Mkr	Ref	Delta	Ref Freq	Ref Amp	Delta Freq	Delta Amp
1	☐	☐	595.000 000 MHz	2.23 dBm	--	--
2	☐	☐	595.010 000 MHz	-55.60 dBm	--	--
3	☐	☐	595.020 000 MHz	-54.87 dBm	--	--

Figure 20: RF Synthesizer Phase Noise Measurement.

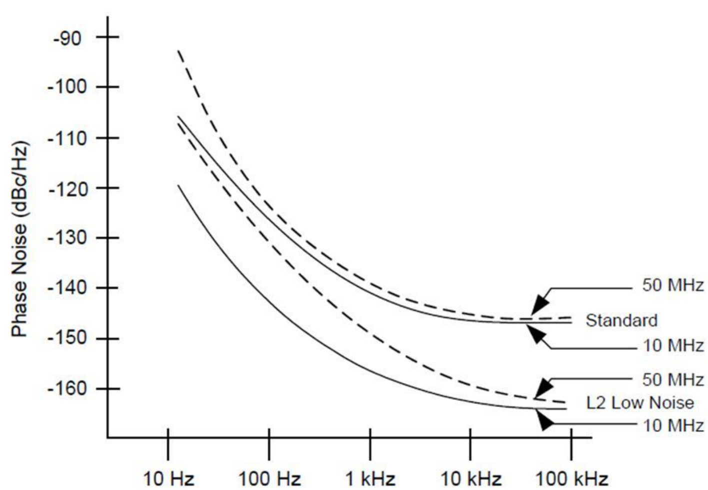


Figure 21: Low Phase Noise Signal Source Comparison [6].

Given the relatively high phase noise level, a measurement was made to determine the stability of the synthesizer's output over a longer time interval. The synthesizer was programmed to output a 595.002 MHz signal which, in turn was sampled using a frequency counter. A total of 400,000 samples were taken over an eight hour period. The measurement set-up is illustrated in Figure 22 and results are plotted in Figure 23.

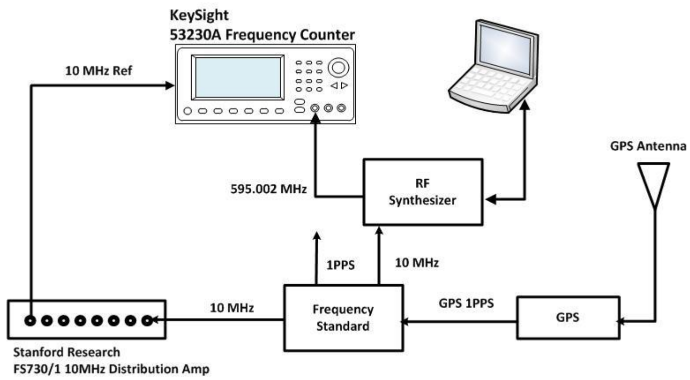


Figure 22: RF Synthesizer Long-Term Stability Measurement Set-Up.

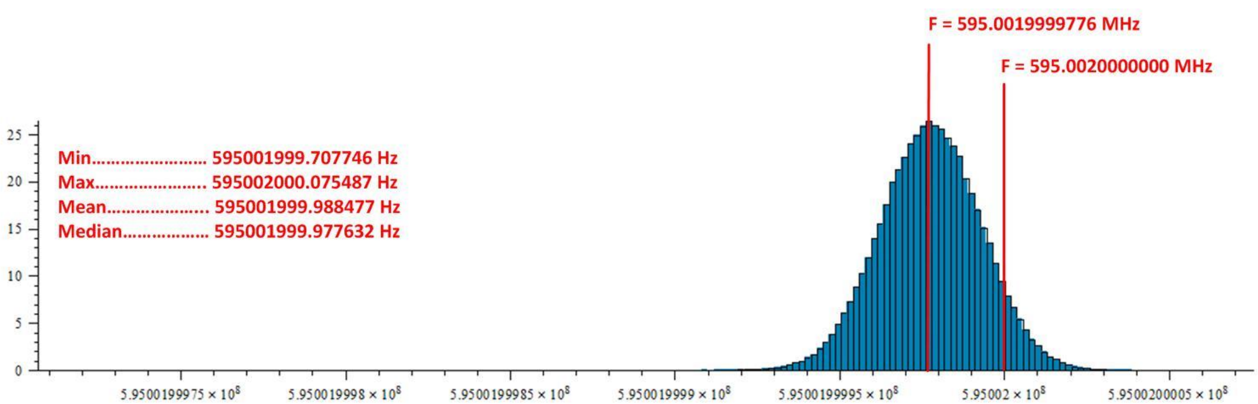


Figure 23: Synthesizer Statistics at 595.002 MHz.

4.3 GPS 1PPS and 10 MHz Signal Timing Comparison

A measurement was made to determine the comparative time delay difference between to different GPS units. The transmitter and receiver instrumentation utilize a GPS generated 1PPS for synchronization of the data collections. The transmitter employees a Trimble Tiny-T GPS unit while each of the receiver units make use of Trimble SMTx GPS units. The basic measurement set-up is illustrated in Figure 24. Each unit's operating statics were monitored using manufacturer supplied software. A screen capture showing the GPS units' operating statistics is shown in Figure 25.

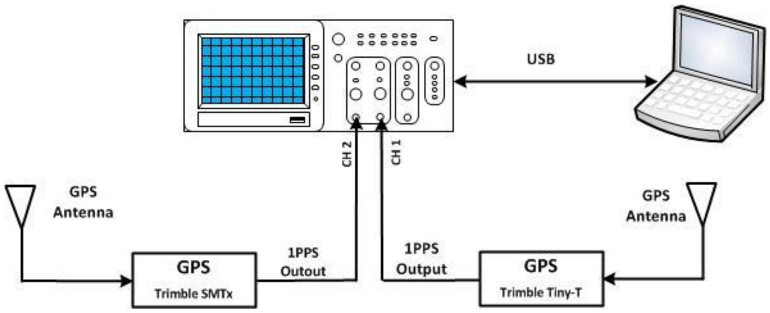


Figure 24: GPS 1PPS Signal Timing Comparison.

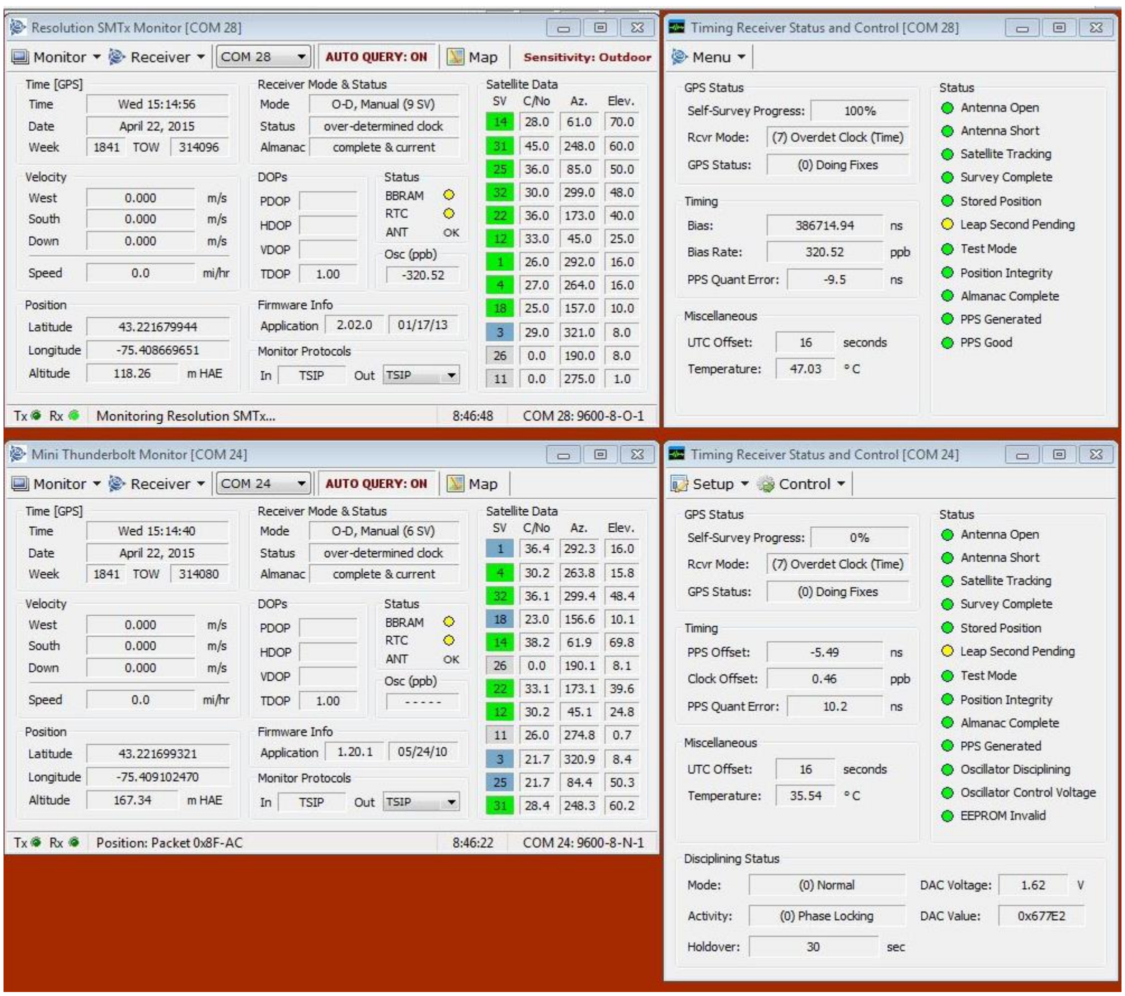


Figure 25: GPS Reports GUI Screen Display.

In this instance the oscilloscope was configured to measure the difference (channel -1's input minus channel-2's input) between the two input signals as indicated in Figure 26 by the red (or "MATH" output) trace. A long-term measurement was made over a ten hour period, with the oscilloscope's display persistence level set to infinite. The result is presented in Figure 27.

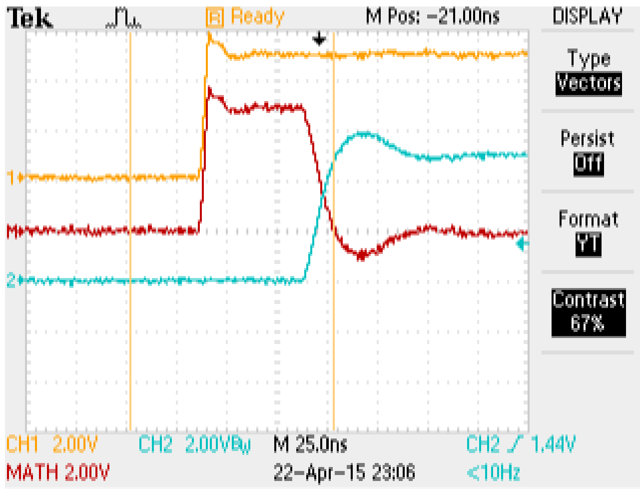


Figure 26: Comparison of Two GPS Units' 1PPS Signal.

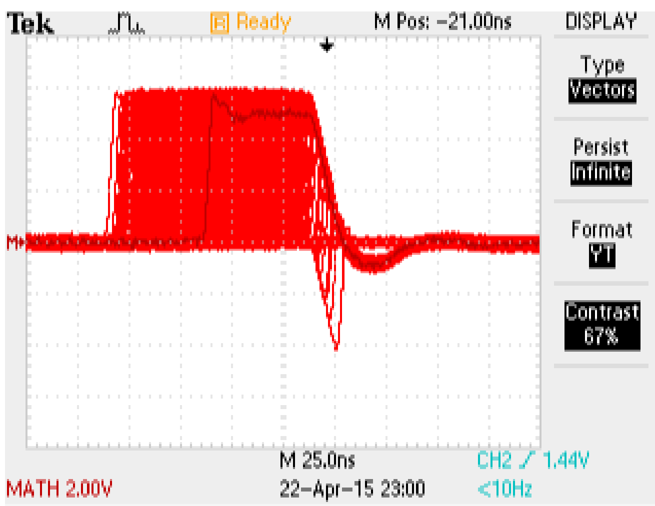


Figure 27: Measured 1PPS Time-Delay Difference For Two Dissimilar GPS Units.

Measurements were made to determine the relative phase offset the 10 MHz signals generated by the GPS and Frequency Standard units. The test set-up is illustrated in Figure 28. Results are presented in Figure 29. One observation worth noting is that the amount of deviation was impacted by the number of satellites being tracked as well as the mix of satellites.

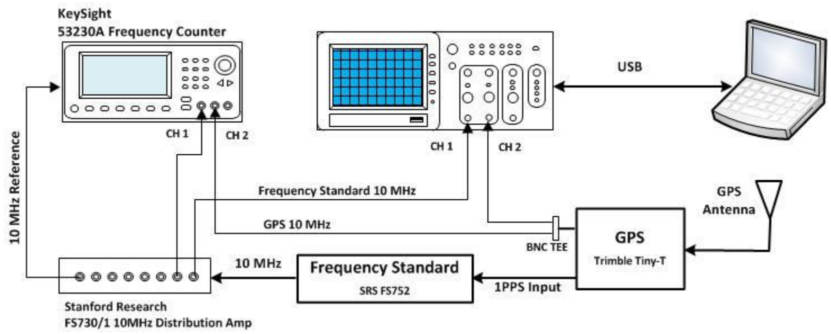
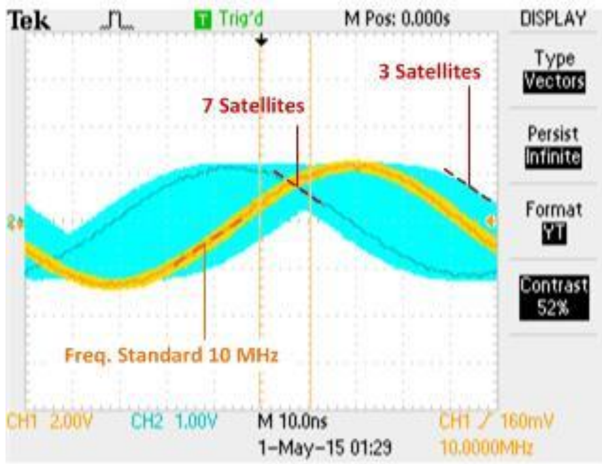
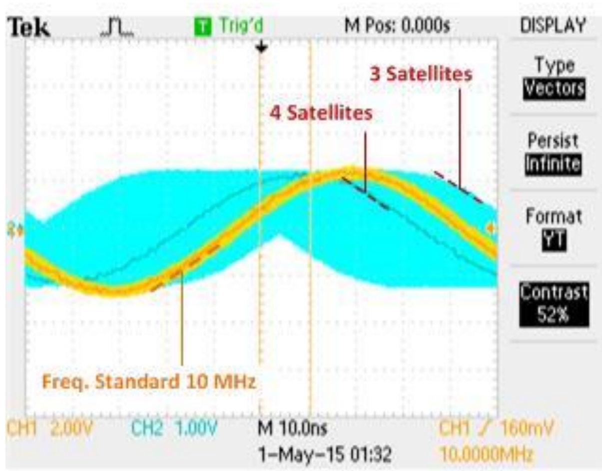


Figure 28: Frequency Standard 10 MHz Stability Measurement Set-Up.



A. Seven satellites tracked by GPS.



B. Four satellites tracked by GPS.

Figure 29: GPS vs Frequency Standard 10 MHz Relative Phase Change.

4.4 Frequency Standard Performance

The performance of the 10 MHz reference is critical to the stability of the transmitter and impacts the ability to accurately synchronize the transmitter and two receivers. Measurements were made to characterize the 10 MHz signal generated by the Frequency Standard and the GPS units.

A measurement was made to determine the stability of the Frequency Standard's 10 MHz output over a longer time interval. Figure 30 illustrates the test set-up. A total of 400,000 samples were taken over an eight hour period. Measurement results are presented in in Figure 31. Two observations are noted: there are a small number of outliers at the lower frequencies, and the distribution has a small tail at the higher frequencies.

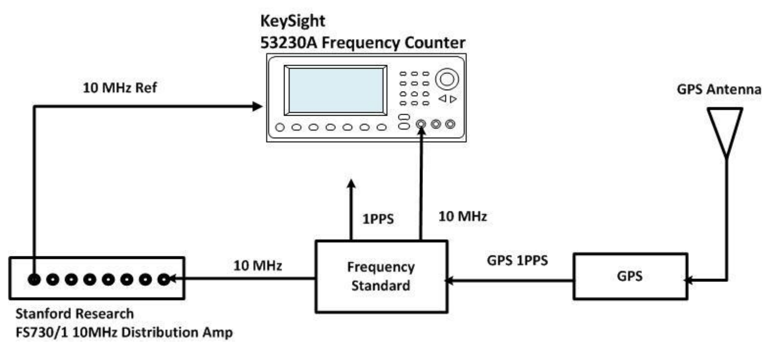


Figure 30: Frequency Standard 10 MHz Long Term Stability Measurement Set-Up I.

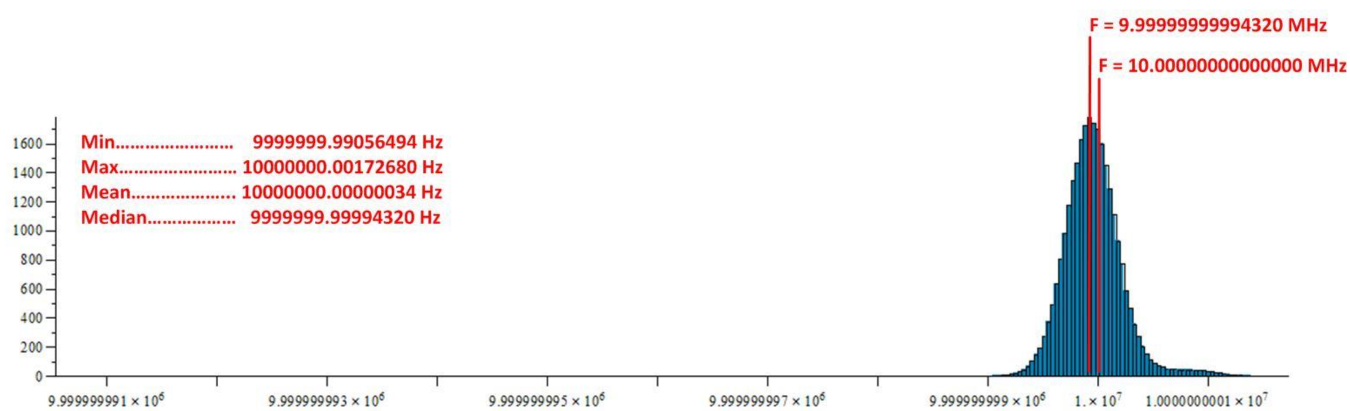


Figure 31: Frequency Standard Statistics at 10 MHz Self-reference.

A measurement was made to determine the stability of the GPS unit's 10 MHz output over a longer time interval. In this case the 10 MHz reference for the frequency counter was sourced from the Frequency Standard. Figure 32 illustrates the test set-up. A total of 400,000 samples were taken over an eight hour period. Measurement results are presented in Figure 33.

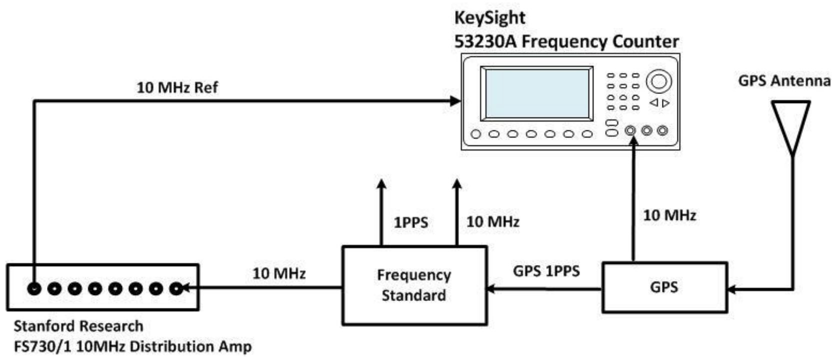


Figure 32: Frequency Standard 10 MHz Long Term Stability Measurement Set-Up II.

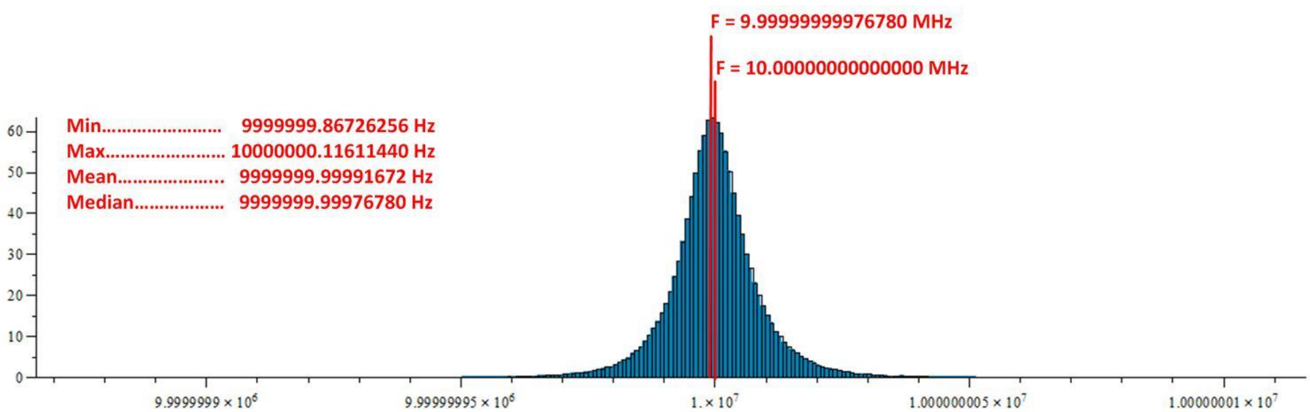


Figure 33: GPS Statistics at 10 MHz with Frequency Standard 10 MHz Reference.

Measurements were made to determine the time delay associated with the 1PPS signal output by the Frequency Standard (SRS FS572). The measurement set-up is illustrated in Figure 34. A screen-capture of the oscilloscope output is provided in Figure 35. A screen capture of the FS752's statistics reports output is provided in Figure 31. The objective of this measurement was to determine whether or not the FS752's time-tag[1] (TT) data could be used to make more accurate time delay measurements given the uncertainty (i.e., jitter) associated with the GPS 1PPS signal.

[1] The value of the time-tag (TT) represents the time difference in nanoseconds between the input 1PPS pulse and the 1PPS output pulse. In other words, the time-tag indicates that the most recent 1PPS input arrived some number of nanoseconds after the 1PPS output.

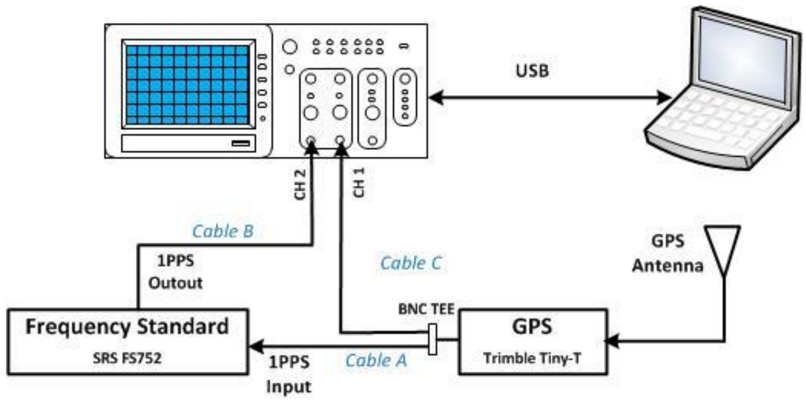


Figure 34: Frequency Standard 1PPS Delay Measurement Set-up.

The 1PPS from the GPS unit is used as the trigger (channel 1) for the oscilloscope measurement. The pulse distortion of the 1PPS trigger signal is due to an impedance mismatch attributed to the use of a BNC-T connection to feed both the Frequency Standard's (50 Ohm) input and the oscilloscope's high impedance input. No 50 Ohm terminations were available in the laboratory at the time of this measurement was made – how sad! The resultant variation in signal amplitude level made setting of the proper threshold level problematic. As a result the threshold level was set at 3 v dc – which was above the required 2.5 v dc level recommended by the unit's manufacturer. The 1PPS signal re-generated by the FS752 is input on channel 2 as indicated in Figure 34.

A cursor was placed at the expect time delay of approximately 8.4 ns (with respect to the triggering delay time). This value was calculated using the respective cable delays (Cable A + Cable B – Cable C = 6.4 ns) and the manufacturer's stated expected internal delay, as measured using reported time-tag data, which is roughly 2 ns. Delay of the FS752 1PPS was monitored along with the reported time-tags (indicated as parameter TT under the 1PPS Control column) as provided on the unit's statistics reports computer monitoring screen. Visual indication showed that the reported time-tag and the measured time delay (relative to the cursor at 8.2 ns) where roughly within +/- 3 ns of each other.

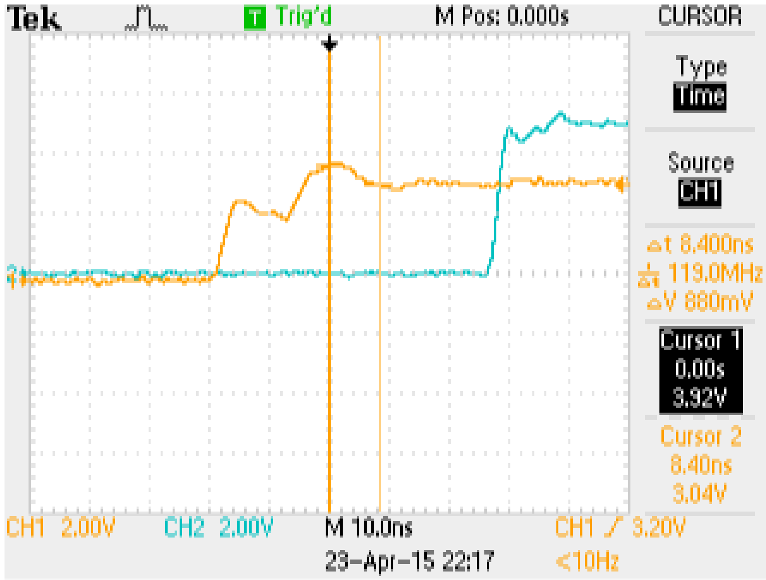


Figure 35: Frequency Standard 1PPS Delay Measurement.

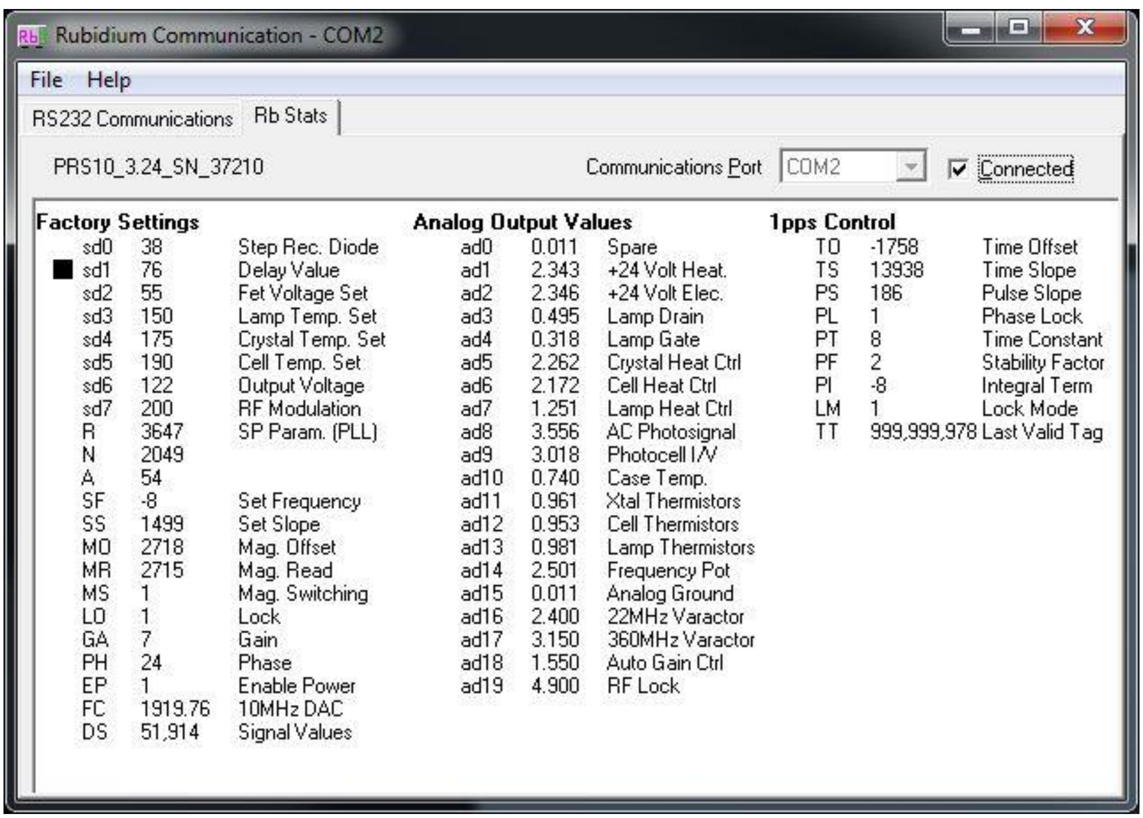


Figure 36: Frequency Standard Operating Statistic Screen.

A measurement was made to determine the stability of the Frequency Standard's 1 PPS output over a longer time interval. Figure 37 illustrates the test set-up. A total of 5900 samples were taken over an eight hour period (with sample gate set to seven seconds). Measurement results are presented in in Figure 38. The manufacturer states [10] that the 1 PPS output has less than 1 ns of jitter. This was confirmed by the measurement results with few outlier samples reported outside the $1 \pm 0.5 \times 10^{-9}$ s interval. One other observation is that the distribution is neither uniform nor Gaussian. The distribution has a central tendency about the one second (1 Hz) mark with two other modes at roughly $1 \pm 2.75 \times 10^{-9}$ s. One conjecture is that this affectation is attributed to the set-points used in the phased-locking control circuitry.

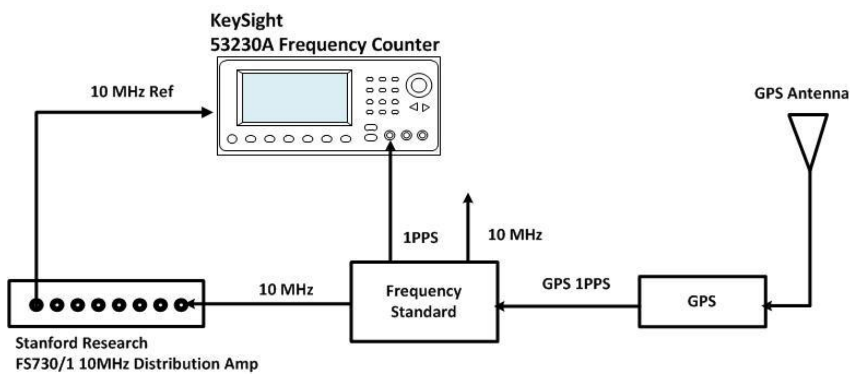


Figure 37: Frequency Standard 1PPS Long Term Stability Measurement Set-Up.

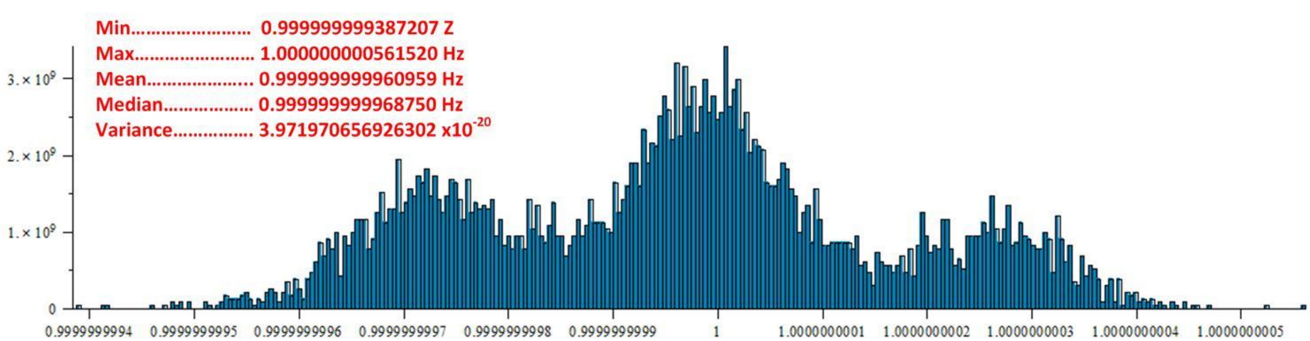


Figure 38: Frequency Standard Statistics 1 PPS.

5.0 Conclusions

The primary objective of this work was to perform basic bench-top performance measurements of COTS system components for use in an FDA antenna designed for communication experimentation. Given the short duration of the effort, and the lack of resources, it was not possible to complete an exhaustive evaluation of operating performance. Testing of low-cost components, that included a waveform generator, signal synthesizer, and GPS timing units were carried out. Test data indicates that the system components are of sufficient quality to allow for preliminary field testing of the proposed FDA design.

6.0 References

[1] P. Antonik, M. C. Wicks, H. D. Griffiths, and C. J. Baker, “Multi-mission, Multi-mode Waveform Diversity”, Proceedings of the IEEE Radar Conference, pp. 580-582, April 2006.

[2] M. Secman, S. Demir, A. Hizal, and T. Eker, “Frequency Diverse Array with Periodic Time Modulated Pattern in Range and Angle”, Proceedings of the IEEE Radar Conference, pp. 427-430, April 2007.

[3] S. Huang, K. F.. Tong and C. J. Baker, “Frequency Diverse Array with Beam Scanning Feature”, Proceedings of the IEEE Antennas and Propagation Conference, San Diego, CA, USA, July 2008.

[4] L. Zhuang, X. Liu, and W. Yu, “Precisely Beam Steering For Frequency Diverese Arrays Based On Frequency Offset Selection”, Proceedings of the International Radar Conference (RADAR ’09), pp 1-4, Bordeaux, France, December 2009.

[5] Wen-Qin Wang, Huaizong Shoa, and Jingye Cai, “Range-Angle-Depenedent Beamforming by Frequency Diverse Array Antenna”, International Journal of Antenna and Propagation, Vol 2012, Article ID 760489.

[6] Vectron Corp., Phase Noise Application Note.

[7] Trimble Mini-T GPS Disciplined Clock Module User Guide, Version 1, Revision B, Trimble Navigation Limited, September 2007.

[8] T346 Embedded Waveform Generator Technical Manual, Highland Technology, October 9, 2013.

[9] Trinity Power Incorporated RF Signal Generator Version 4.8 User Manual.

[10] Stanford Research, Model FS725 Rubidium Frequency Standard Operation and Service Manual, page 6.

7.0 List Of Symbols, Abbreviations, and Acronyms.

COTS	Commercial-Off-The-Shelf
CW	Continuous Wave
dB	Decibel
dBc	Decibel below Carrier
DDS	Direct Digital Synthesizer
FDA	Frequency Diverse Array
GPS	Global Positioning System
Hz	Hertz
IF	Intermediate Frequency
LPI	Low Probability of Intercept
MHz	Mega-Hertz
PPL	Phase Locked Loop
PPS	Pulse Per Second
PRI	Pulse Repetition Interval
PRF	Pulse Repetition Frequency
RF	Radio Frequency
USB	Universal Serial Bus
WG	Waveform Generator

APPENDIX A: RF SYNTHESIZER COMPARISON

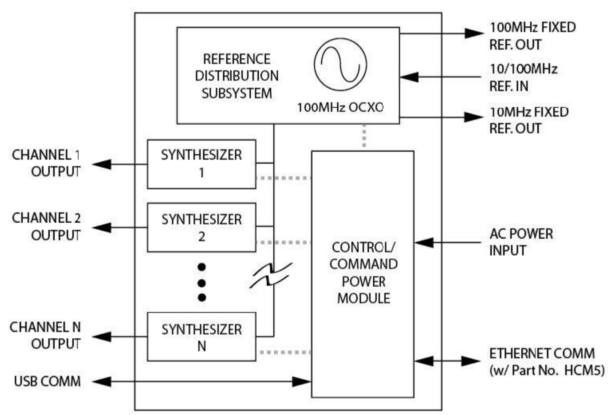
Device	Phase Noise	Jitter
Trinity Power Incorporated (TPI) **RF Signal Generator** **Cost/Channel ≈ $280**	595 MHz, 10 kHz offset ≤ -88 dBc/Hz 2.4 GHz, 10 kHz offset ≤ -89 dBc/Hz	< 0.4 ps rms
Holzworth HS9000 **Multi-Channel RF Synthesizer** **Cost/Channel ≈ $5,100** 	100 MHz, 10 kHz offset ≤ -153 dBc/Hz 500 MHz, 10 kHz offset ≤ -139 dBc/Hz 1.0 GHz, 10 kHz offset ≤ -133 dBc/Hz 2.0 GHz, 10 kHz offset ≤ -127 dBc/Hz 3.0 GHz, 10 kHz offset ≤ -123 dBc/Hz 4.0 GHz, 10 kHz offset ≤ -121 dBc/Hz 6.0 GHz, 10 kHz offset ≤ -117 dBc/Hz	155 MHz , 60 fs 622 MHz , 61 fs 2.488 GHz , 55 fs
Agilent N5181A 501 **RF Analog RF Generator** **9 kHz to 1 GHz** **Cost/Channel $7,830** 	1.0 GHz, 20 khz offset ≤ -146 dBc/Hz	
Stanford Research SG382 **RF Signal Generator** **2GHz** **Cost/Channel $ 3900** 	10 MHz, 10 kHz offset ≤ -135 dBc/Hz 100 MHz, 10 kHz offset ≤ -118 dBc/Hz 1.0 GHz, 10 kHz offset ≤ -108 dBc/Hz 2.0 GHz, 10 kHz offset ≤ --105 dBc/Hz	< 300 fs rms
EM Research **Frequency Synthesizer** **Cost/Channel $ 800** 	4.0 GHz, 10 kHz offset < -105 dBc/Hz	

Table 3: RF Synthesizer Cost Comparison.

Holzworth HS9000 Series Multi-channel RF Synthesizer – provides up to eight independently tunable synthesizer channels in a single 1U chassis. Figure 39 shows an eight (8) channel unit. The system configuration outlined herein calls for a four (4) channel unit which is available as a specified option. The cost of a four channel unit is $23,000. However, numerous configurations are available which will impact the final price of the unit.

Reference: http://www.holzworth.com/synthesizers-multi.htm .

A. HS9000 Series Unit



B. Functional Diagram

Figure 39: Multi-Channel RF Synthesizer.